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COMPARATIVE ANALYSIS OF TWO CBN GRINDING WHEELS PERFORMANCE IN NODULAR CAST IRON PLUNGE GRINDING

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Abstract. *This research analysed and compared the output parameters in cylindrical grinding of nodular cast iron GGG-70 (medium hardness of 270 HB) using two CBN grinding wheels with same specifications and characteristics, but presenting an accentuated difference on the abrasive grains' friability. The various applicability attributed to the nodular cast iron are due to its versatility in respect of mechanical properties just by the application of heat treatment, without adding alloying elements. Also, due to its high fluidity, the part can be very close to the final dimensions, being necessary in most cases only finishing processes. Generally grinding gives the part its final form. To optimize cost production, machining processes became the focus of scientists and engineers. The correct selection of the grinding wheel could determine the success of an operation as its properties influence productivity and workpiece quality decisively. In this way, the performance of each grinding wheel was analysed taking into account the results of average surface roughness, average power and G-ratio (obtained through the diametrical wheel wear). It was observed that the less friable wheel produced better surface roughness and less wheel wear than the more friable wheel, although the average power on the process was higher on the more friable wheel, what can be explained by the constant creation of new cutting edges, facilitating material removal.*

Keywords: *Cylindrical plunge grinding, CBN, nodular cast iron, friability.*

1. INTRODUCTION

Grinding is one of the most important machining processes in the production of high-precision and high-quality mechanical and optical components (Oliveira *et al.*, 2009). It is therefore usually the last process in a sequence of machining operations and the workpiece already has a high added value when it reaches this stage, making its rejection very expensive.

In comparison to other processes like turning or milling, the material removal rate of grinding is relatively low, which results in high process duration and cost-intensive processes. Thus, this costly process only is carried out, if the demands on a workpiece require it, making the economic efficiency of the grinding process an important factor (Ahrens *et al.*, 2017).

The right choice of the grinding wheel determines the success of a grinding operation. According to the grinding wheel properties, a certain level of productivity and workpiece quality can be achieved considering the process parameters and the workpiece material (Denkena *et al.*, 2016). In this way, a study to determine the effect of the variation of each property of the grinding wheel along with the parameters of the process to obtain the best combination is very important. A controllable property of the abrasive grains refers to its level of friability (the opposite of toughness), which can be understood as the tendency of an abrasive grain to fracture under compression.

As abrasive grains' micro-fractures produce sharp new edges, friability can be advantageous for maintaining grinding wheel sharpness. In general, more friable abrasive grains result in lower grinding forces. However, more friable abrasives tend to accentuate the wheel wear in comparison to the less friable ones, what can be disadvantageous in terms of cost with new tools, but can also be advantageous in the grinding of some materials and in some operations (Rowe, 2014).

This paper presents a comparative analysis of the performance of two CBN grinding wheels with the same specifications in the cylindrical plunge grinding of GGG-70 nodular cast iron at different infeed rates, highlighting their advantages and disadvantages based on the results obtained. The difference between the tools is the accentuated difference of the friability level of the abrasive grains.

It is known that increasing infeed rate, with other speeds constant, there is also an increase on the grinding forces and roughness. However, there is an advantage of reducing the specific energy. In this way, the process becomes more energy efficient up to the point that the high infeed rate leads to high wheel wear and low grinding ratio (G-ratio) (Rowe, 2014).

The material studied in this research was the nodular cast iron, which was introduced into the market long ago, but has been under continuous development in recent decades. This material has broadened its scope of applications due to the lower costs and the considerable range of possible properties possible to obtain, leading to a significant growth in the global production rates of this material (Sosa and Echeverría, 2015).

Nodular cast iron can be used in several parts in which mechanical requirements and reliability are crucial attributes. Some examples are: auto parts (crankshafts, suspension parts) and several industrial machine parts (Sosa and Echeverría, 2015), such as gears, piston sleeves, camshafts, valves and pumps, among several other components, due to its excellent combination of high ductility, high strength, low wear and relatively low production costs. The machining costs involved in the manufacture of nodular cast iron crankshafts are up to 50% lower than those of forged steel crankshafts, which is one of the main reasons why most companies use nodular cast iron instead of steel for this kind of part.

The production of nodular cast iron takes a considerable part of the cast iron market. However, most of the components made of this material can't be used as they come out of the casting process and must be machined in order to have better surface, dimensional and geometrical quality. In this way, it's very important to evaluate the performance of the tools used in the machining of this material (Aurich *et al.*, 2016).

1.1 CBN grinding wheel

Between the most used materials for the abrasive grains of the grinding wheels, the CBN is the second hardest of the scale and is widely used for grinding steels. Although CBN is way more expensive than conventional abrasives, total costs can be substantially lower. Also, CBN is increasingly replacing conventional abrasives for precision grinding due to its low rate of wear and the ability to hold close size tolerance on the parts produced (Rowe, 2014).

In comparison to diamond, CBN has the advantage of higher thermal stability and in the beginning, this material was bonded in metal or resin bonds, however, vitrified bonds featured the intrinsic advantages of CBN best. Also, thermal induced damage is much less likely to occur with CBN tools in comparison to conventional abrasives since not only the specific grinding energies are normally smaller, but the abrasive grit material CBN has also a much higher thermal conductivity (e.g. 35 times bigger than that in corundum). The lower heat flux into the workpiece results in smaller tensile stresses and even favorable compressive stresses at the surface (Linke, 2016).

Due to its high level of hardness and thermal and chemical resistance, CBN is considered a high-performance abrasive. In comparison to conventional abrasives, CBN has the ability to cut maintained over a longer period of time. Also, an individual CBN grain will exhibit a life hundred times that of conventional grain. Due to its inherent sharpness, CBN tends to machine cooler, providing high surface integrity and superior surface finish (Kopac and Krajnc, 2003).

1.2 Friability

Whilst hardness provides a measure for the tendency of grain to wear by attrition on the atomic scale, friability (or its inverse term "fracture toughness") provides a measure for the loss of abrasive due to breakdown by fracturing or splintering of the grain typically at the micron level (micro-fracture) or greater (macro-fracture). The degree of the fracture depends on grain properties such as crystal size and morphology, impurities, inclusions and pre-existing cracks, and shape. It is also highly dependent on the level and nature of the forces applied to the grain during grinding and from factors in

the grinding environment such as thermal shock from coolant. Attritious wear leads to the creation of wear flats that highly increases the force exerted on the grain and in turn leads to increased levels of fracture (Jackson and Davim, 2011).

Regarding ways to measure this property, the “toughness index” (TI) is one industrial measure, which refers to the resistance of the grit against breakage and crack propagation, and is often measured under dynamic conditions. Also, temperatures during grinding can induce grit defects that change the grit breaking behavior, so “temperature toughness index” (TTI) is another useful measure. On the other hand, it is also possible to analyze it with the “friability index” (FI), which measures the loss of abrasive material by splintering (Linke, 2016).

Manufacturers of superabrasives evaluate the grit fracture behavior by impact strength tests, known as friability test or friatester. A grit sample with a defined weight and a steel ball are encased in a capsule, which is then shaken with a defined cycle number. The impact load breaks a portion of the grits. The percentage of the non-destroyed grits is defined as toughness index (TI). Usually, diamond grit manufacturers qualify their grits by room temperature toughness (TI) and thermal toughness after heating (TTI), for example at 1000 °C (Linke, 2016).

On the one hand, grits that are too tough for a certain application will become dull and increase friction. This leads to unnecessary thermal damage of the workpiece material and the danger of process vibrations. On the other hand, too friable grits wear away quickly resulting in short tool life and possibly form errors.

Ideally, the grain should fracture creating the loss of relatively fine particles typically at the micron or sub-micron level; a process termed “micro-fracturing”. The remaining portion of the grain should remain sharp and able to cut. If the grain is too tough relative to the bond holding it, or the grinding force/grain is extremely high, then the grain can undergo total break-out or loss without doing any useful work. If the bond is strong enough to hold the grain but there are high grinding forces/grain, and/or the grain crystallite size is large, then the fracture is often more one of coarse loss of grain by “macro-fracturing” still without the full amount of possible useful work being obtained. On the other hand, if the grain is much weaker than the bond and/or prone to high attritious wear due to mechanical, heat or chemical wear, then “glazing” occurs resulting in the creation of wear flats, high grinding forces and increased interface temperature. Higher forces will lead in turn to more fracture (Jackson and Davim, 2011). Fig. 1 shows the grain/bond breakdown modes in grinding wheels:

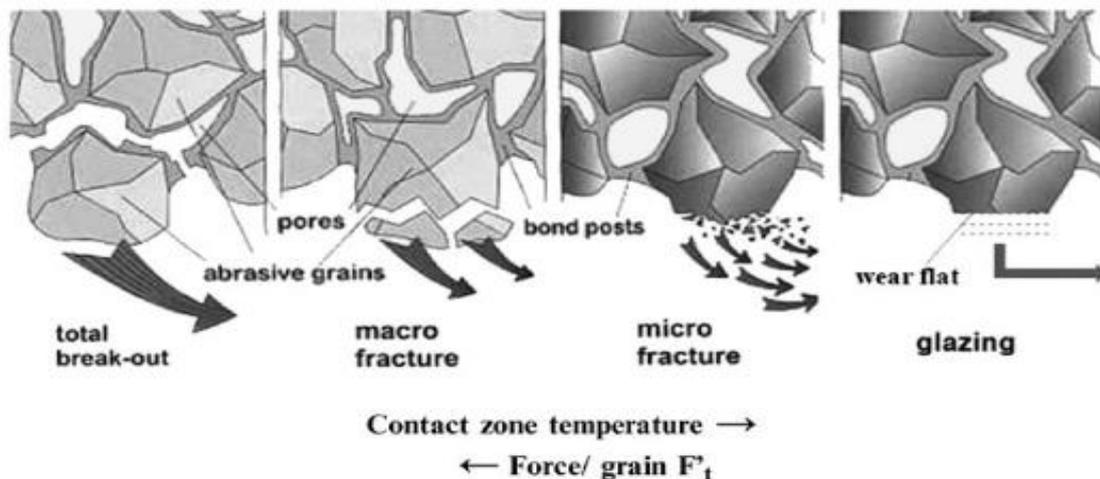


Figure 1. Grain/bond breakdown modes in grinding wheels (Jackson and Davim, 2011).

In this way, Linke (2016) concludes that as optimum, the grits should have a controlled breakdown behavior, so that they regenerate sharp cutting edges and the tool works in the so called self-sharpening mode.

Usually, hard and friable abrasive grains are applied in precision grinding, whereas tougher abrasive grains are more suitable to operations with large amount of material removal (Malkin and Guo, 2008).

1.3 Nodular cast iron (ductile iron)

Among the iron-carbon alloys, the cast iron constitutes a group of fundamental importance to the industry, not only due to the characteristics inherent to the material itself, but also because, through the introduction of alloying elements, application of suitable heat treatment and development of the nodular cast iron, the use of this material became feasible in applications that were, to a certain extent, exclusive to steels (Chiaverini, 2008).

In cast irons that contain graphite, the microstructure is configured to a matrix similarly to steel (ferrite, pearlite, martensite, among others) and also has graphite particles. Graphite has very low mechanical strength and its presence can be considered as a discontinuity of the matrix, presenting a stress concentration effect. The form in which the graphite presents itself has a great effect on the mechanical properties of the material. For example, the spheroidal shape results in a lower stress concentration effect, whereas the more acute forms (known as graphite flakes) have high stress

concentrations. Nodular cast irons have greater mechanical strength and ductility in comparison to grey cast iron, presenting mechanical characteristics that approximate to steel (Guesser, 2009).

Since ductile iron parts can achieve shapes and dimensions very close to the final ones, the machining operations performed are for finish purposes. Surface grinding is the most common finish machining process employed and involves abrasive chip formation, a process that produces a great amount of heat and leads to plastic deformations that modify material surface properties (Sosa and Echeverría, 2015).

The ductile iron also has a better strength/weight ratio in comparison to the low carbon steel. This enables in various cases that a ductile iron part substitutes a steel one, presenting a weight reduction (Guesser, 2009).

Regarding the nodular cast iron, in general this material presents an easy machinability. The presence of graphite about 11-12% helps in the chip breakage, avoiding partly the adhesion of the chip in the tool (Guesser, 2009).

2. EXPERIMENTAL SETUP AND PARAMETERS MEASUREMENT

With the objective of comparing the effect of the variation of the friability level of the abrasive grains of the grinding wheel, two vitrified bonded CBN wheels with an accentuated difference on the toughness index (TI) were used. The output parameters of the process allowed to analyze the advantages and disadvantages of each grinding wheel.

The grinding wheels used were specified as CBN GS (SNB151.GS Q12 VR2) and CBN GL (SNB151.GL Q12 VR2), both with dimensions 350 mm (outside diameter) x 19 mm (thickness) x 127 mm (hole diameter). The abrasive grains were donated by the group *Saint-Gobain Ceramic Materials – Surface Conditioning*.

The GS wheel is the most friable one and the GL wheel is the toughest one (Fig. 2).



Figure 2. Abrasive grains of the CBN GS grinding wheel (left) and CBN GL grinding wheel (right), names given by the manufacturer *Nikkon Ferramentas de Corte Ltda*.

The CBN GS abrasive grain is a black, irregular shaped crystal structure which presents high level of friability. Most particles macro fracture, but expose multiple cutting edges. On the other hand, CBN GL abrasive grain is a very tough amber colored, blocky mono crystalline CBN with very high fracture strength.

The workpieces were made of nodular cast iron GGG 70 with average Brinell hardness (HB) of 270 acquired from *METALRENS*. They were ring shaped with an external diameter of 92 ± 0.1 mm, internal diameter of 30 ± 0.1 mm and thickness of 5 ± 0.1 mm.

The tests were performed on a CNC cylindrical grinding, model RUAP 515H, made by *SULMECÂNICA* and the dressing was performed with a multi-point diamond dresser, from *Master Diamond*. The dressing conditions were maintained constant and the operation was performed to uniform the surface of the grinding wheel.

The lubri-refrigeration system used was the conventional one, in a similar system to the most used in industry nowadays. The fluid used was the *QUIMATIC ME-I* semi-synthetic coolant with 2.5% concentration in water. The application was done through two nozzles directed to the grinding wheel/workpiece contact area.

Three infeed rates were used - 0.5; 1.0 and 1.5 mm/min. To obtain greater statistic reliability, the procedures were done three times for each feed rate. Therefore, a total of eighteen samples were studied (2 grinding wheels, 3 infeed rates and 3 replications of each experiment).

It was removed 28 mm of material from the external diameter of the workpiece (280 grinding cycles removing 100 μ m of material per pass), resulting in a final external diameter of 64 mm.

The output variables analyzed were surface roughness, grinding power and diametric wheel wear (along with G-ratio). The experimental conditions are shown in Tab. 1:

Table 1: Experimental conditions.

Experimental conditions	Values
Feed rate (v_f)	0.5; 1.0; 1.5 mm/min
Workpiece peripheral speed (v_w)	0.39 m/s (initial) 0.27 m/s (final)
Cutting speed (v_s)	32 m/s
Spark-out time	8 seconds
Dressing depth	80 μm (2 $\mu\text{m}/\text{pass}$)
Cutting depth (a)	0.05 mm
Grinding width (b)	5 mm
Cutting fluid flow rate	17 L/min

It is important to note that the initial workpiece peripheral speed is higher than the final due to the considerable reduction of its diameter during the process. However, this variation of speed doesn't interfere with the purpose of this study, which is compare the effect of friability on the grinding wheels, since both were submitted to the same conditions.

2.1 Diametric wheel wear and G-ratio

Due to process forces and temperatures during grinding, a grinding wheel is subject to modification by a process of wheel wear. Wear leads to changed process conditions and quality deviations in the component. In plunge grinding, where the wheel profile is reproduced in the ground component, profile deviations lead to workpiece shape defects. Also, a loss of grinding wheel sharpness leads to higher grinding forces and temperatures, which may result as well in shape and position errors (Marinescu *et al.*, 2016). In this way, having a controlled wheel wear is very beneficial to the process.

The G-ratio can be seen as a measure of the ability of a grinding wheel to remove material. An efficient grinding wheel is able to grind an easy-to-grind material for a long time with only a small amount of wheel wear, which corresponds to a high G-ratio (Rowe, 2014). This parameter is defined as the volume of material removed divided by volume of wheel wear, as seen in Eq. (1):

$$G = \frac{V_w}{V_s} \quad (1)$$

V_w is the volume of material removed and V_s the volume of wheel wear.

The G-ratio depends on the machined material, tool design, grinding operation and parameters, cooling lubricant, machine tool, among other variables. In this way, no certain value can be given for a generic application, but literature provides ranges of G-ratios. For example, in precision grinding of steel, maximum values of G-ratio of about 50 mm³/mm³ can be reached with alumina wheels and G-ratios of more than 10000 mm³/mm³ with CBN wheels (Linke, 2016).

The grinding wheel's diametric wear was also measured with the *Surtronic 3+* roughness gage, but using a cylinder to print the grinding wheel profile. The method consisted in grinding a cylinder after every two testes removing a certain volume of material, since due to the 5 mm thickness of the workpiece and 19 mm thickness of the grinding wheel, it was possible to use each side of the wheel to grind each workpiece in regions properly spaced without interference of the wheel wear in each other (Fig. 3). With that, the existing unevenness between the worn and non-worn surface of the wheel was transferred to the cylinder, which was subsequently measured.

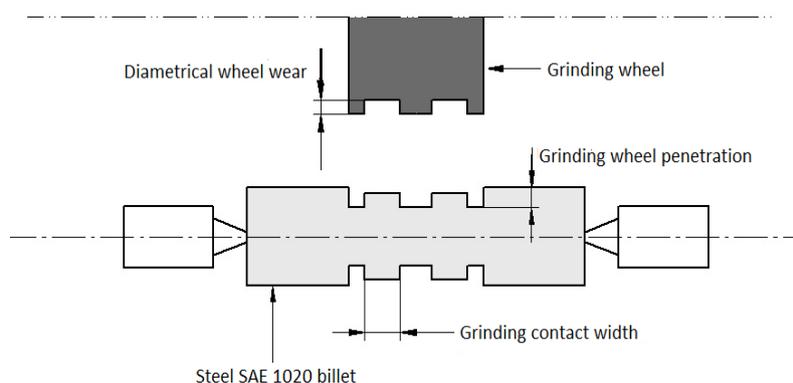


Figure 3. Printing of the grinding wheel profile on the cylinder.

Since in the machined zone the wheel worn with consequent reduction in its diameter in relation to the non-machined zone, the cylinder in which was printed the grinding wheel profile presented larger diameter on the worn zones of the wheel and smaller diameter on the zones that the wheel didn't touch the workpiece.

After this procedure, the wheel profile of wear was generated using the software *Taylor-Hobson TalyMap* and measured with the roughness gage, which was programmed to pass longitudinally over 4 mm of the cylinder. With the profile obtained, it was used a software tool to measure the difference in depth between the corresponding average points of the machined and non-machined zones in the profile to acquire the value of the diametric wheel wear.

In possession of the diametric wheel wear values, it was possible to calculate the G-ratio for each condition. Based on a constant volume of removed material and workpiece thickness in all the tests, and considering the initial diameter of the wheel to be approximately 350 mm, which is a reasonable approximation considering the equation terms, the G-ratio can be calculated using Eq. (2):

$$G = \frac{\frac{(\pi D_w^2 - \pi d_w^2)}{4} * t}{\frac{(\pi D_r^2 - \pi d_r^2)}{4} * t} = \frac{(92^2 - 64^2)}{(350^2 - d_r^2)} \quad (2)$$

D_w is the initial workpiece diameter, d_w is the final workpiece diameter, D_r is the initial wheel diameter, d_r is the final wheel diameter, and t is the workpiece thickness. The value of the G-ratio for each condition was obtained substituting the value of d_r in the last term of the expression, which was obtained through the differential value measured in the wheel profile between the worn and not worn regions.

2.2 Average surface roughness (R_a)

The quality of the surface generated by grinding determines many workpiece characteristics such as the minimum tolerances, the lubrication effectiveness and the component life, among others. A typical surface is characterized by clean cutting paths and plowed material to the sideway of some grooves. When considering all the factors, a complete prediction of the surface topography is complicated. A typical parameter that has been used to quantify the quality of a surface topography is the surface roughness (Hecker and Liang, 2003).

The arithmetic mean value of surface roughness (R_a) can be defined as the arithmetic average of the absolute values of the deviations of the surface profile height from the mean line within the sampling length l .

Furthermore, the analysis of this parameter is extremely important, since it is well known that the surface finish can significantly affect the resistance of the components when they undergo fatigue cycles. Moreover, the surface finish of the workpiece is directly connected to some material's properties, such as: friction coefficient, abrasion and lubrication capacity, thermal conductivity, mechanical resistance and others (Silva *et al.*, 2013). A good example of a nodular cast iron component that undergoes grinding and fatigue cycles is the crankshaft of automobile engines.

The average roughness was obtained from measurements taken with a *Surtronic 3+* roughness gage, from *Taylor-Hobson*, with gauge movement in the axial direction, using a cut-off length of 0.25 mm and a total path (l_n) of 1.25 mm.

According to Rowe (2014), the some of the factors that interfere on the roughness of the ground workpiece are: irregular grain spacing; irregular grain depths; wheel dressing; wheel wear; wheel loading; elasticity of the wheel; spark-out; grinding fluid, among others. It is important to notice that the roughness is highly dependent on the wear level of the abrasive grains. Since the only variable in this study is the abrasive grain itself, the roughness can be analyzed directly as an effect of the change of this variable.

2.3 Grinding power

Grinding is a complex and highly non-stationary process owing to a huge number of irregular cutting edges in abrasive tools. The abrasive tool and process condition monitoring is a well-recognized approach to track process change and analyze tool condition. In this way, power monitoring, is an easy and convenient way to obtain useful information for the grinding process since it presents relative low cost and there is no special design of complex fixturing and modification of machine tool to be used (Tian *et al.*, 2017). Also, the power monitoring is very used in the industrial environment to detect collision and to prevent machine overload (Tönshoff and Inasaki, 2001).

In this study, the emphasis during data acquisition was on power related data, which was collected by means of a power module containing two Hall effect sensors, one for current and other for voltage measurements. This procedure enables data to be acquired in real time during the grinding process. The signals obtained in these sensors were multiplied by an integrated circuit, resulting in the instantaneous power. A computer equipped with an A/D data acquisition board and LabVIEW 7.1 software was used along with the power module. The data collected in real time was simultaneously recorded in the computer in the form of voltage (V), which was then converted into watts (W) by proper mathematical manipulation on MATLAB software.

3. RESULTS AND DISCUSSIONS

3.1. Diametric wheel wear and G-ratio

The average values obtained for the diametric wheel wear for each condition are shown in Fig. 4:

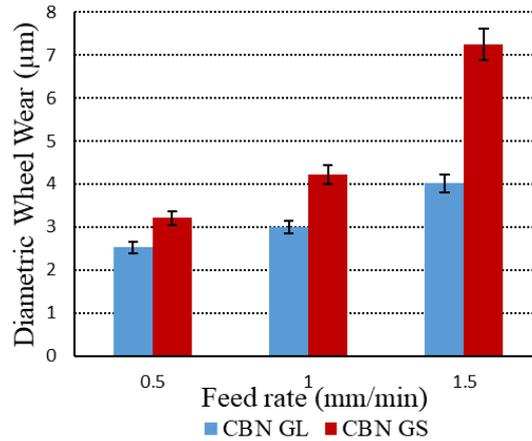


Figure 4. Diametric wheel wear in each experimental condition.

Figure 4 indicates that the diametric wear of the CBN GL grinding wheel was considerably lower than that of the CBN GS at all the feed rates. From this data it is possible to calculate the G-ratio for each condition. The obtained G-ratios are shown in Fig. 5.

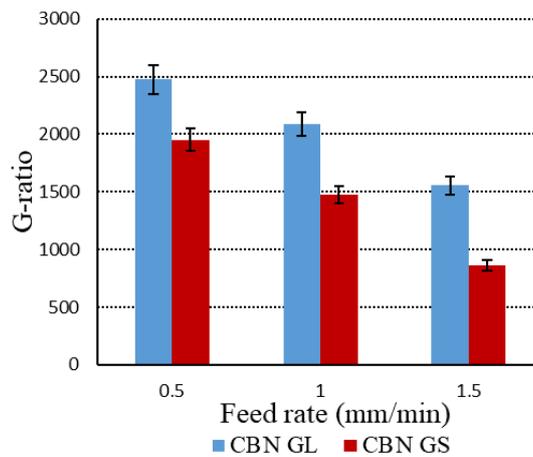


Figure 5. Value of the G-ratio in each experimental condition.

An analysis of Fig. 5 reveals an interesting behavior regarding the G-ratios of the CBN GL and CBN GS grinding wheels. At a feed rate of 0.5 mm/min, the G-ratios differed by 526.2, at 1.0 mm/min they differed by 608.283, and at 1.5 mm/min they differed by 694.232. This behavior indicates a growing difference between the G-ratios of the two wheels, i.e., the ratio decreased considerably at every 0.5 mm/min of increase in feed rate. However, the CBN GL wheel showed an 80 to 90 units greater difference in the values between wheels compared to the difference observed in the previous feed rate, i.e., the difference in G-ratios increased along with increasing feed rate. This may indicate that the CBN GL wheel is even more suitable for conditions which require higher grinding forces in the analyzed range.

The G-ratio is directly related to the friability of the grinding wheels. Higher friability indicates more fracture processes and, also, more wheel wear for the same amount of material removal. That is the reason why the G-ratio was higher on the CBN GL wheel and lower on the CBN GS. Also, it is important to observe that, at higher feed rates, the difference between both wheel values was accentuated. The reason why that occurs is that when the wheel is submitted to higher forces, the fracture processes gets even more accentuated on the friable wheel and wear becomes even more expressive than in the tougher wheel. In other words, high toughness indicates low percentage breakdown of the abrasive grains and, consequently, the G-ratio was found to be higher at the analyzed range.

Taborga (2002) also analyzed in his research the G-ratio when the only variation was in the specific removal rate, which was controlled by means of a variation of the feed rate. The result obtained by the author was that with the increase of the specific removal rate, the diametric wheel wear also increased, and thus the G-ratio decreased. The explanation given for this phenomenon was that with an increase of specific removal rate there was also an increase in the cutting depth per wheel revolution and in the non-deformed chip thickness and, consequently, in the chip's momentane section, increasing the mechanical and thermal solicitations in grinding per grain, leading to an increase of diametric wheel wear.

Therefore, it is possible to say that the results obtained in this research for the variation of diametric wheel wear according to the variation in feed rate are coherent with the expected results.

3.2. Surface Roughness

After the data acquisition, it was possible to plot a graph comparing the average roughness values between the grinding wheels, as shown in Fig. 6:

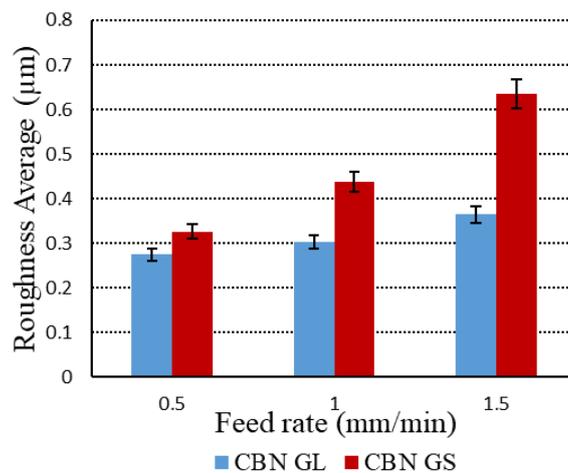


Figure 6. Average surface roughness of the two grinding wheels resulting from each feed condition.

Regarding the feed rate, it was observed that an increase of the feed rate resulted in higher values of surface roughness for both grinding wheels. This can be explained by the fact that higher feed rates result in higher values of equivalent chip thickness and material removal rates. In turn, this causes increased stress on the abrasive grains and longer wheel-workpiece contact, leading to directly proportional increase of cutting forces and power.

Since feed rate and grain friability were the only variables, it was found that, at the same feed rate, the surface roughness of the CBN GL grinding wheel was lower in all the experimental conditions.

Taborga *et al.* (2003) also analyzed the surface roughness in function of the feed rate, but using silicon carbide and aluminum oxide grinding wheels. These authors also obtained that with an increase in feed rate and a decrease in cutting speed there is an increase in surface roughness. The authors' explanation for this phenomenon was that, when the feed rate is increased and, consequently, the non-deformed chip thickness is increased due to the increase in feed per workpiece revolution, the surface roughness becomes higher.

It was also possible to notice a pattern in the differences in surface roughness between each wheel as the feed rate increased, in such a way that the difference in average surface roughness obtained for the samples of each wheel under the same condition was higher as the feed rate increased.

In other words, as the feed rate increased, it is preferable to use a wheel with a tough grain in order to obtain a better surface roughness. Regarding this parameter only, the CBN GS wheel works better in lower feed rates or under lower cutting forces. Regarding the CBN GL wheel, despite it showed an increase in surface roughness with the increase of feed rate, the difference in its values is not as high as in the other case, making this wheel a good candidate for operations that demand higher forces.

The reason for such difference in the results between the grinding wheels is deeply connected to the difference in grain friability. The CBN GL wheel, having tougher abrasive grains, shows a lower total tool wear (as seen in section 2.1), and thus a more regular wear of the abrasive grains along its length. Because of that characteristic, the CBN GL wheel can resist higher feed rates and cutting forces without showing high tool wear, being able to produce high quality and regular surfaces on the workpieces under the tested conditions. On the other hand, the CBN GS wheel, which is more friable, showed higher tool wear, which resulted in a more irregular distribution of the grains along its length, causing higher average surface roughness compared to the other wheel. Due to its high friability, as the feed rate increased, its wear also increased, seeing that under higher forces a friable grinding wheel fracture even more frequently, resulting in an even more accentuated increase in average surface roughness.

3.3. Grinding power and other analyses

From the graphs obtained for power in function of time, it was possible to calculate an average power value for each condition and plot the graph shown in Fig. 7:

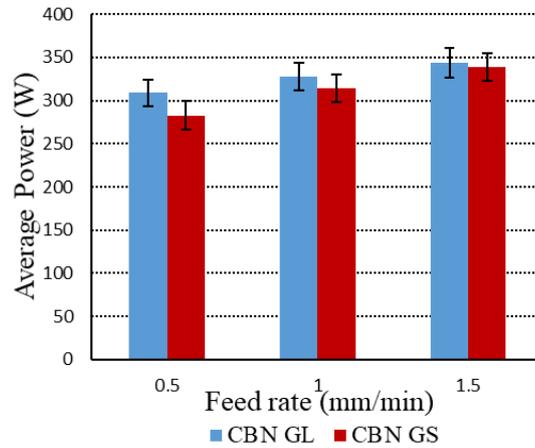


Figure 7. Average grinding power in each experimental condition.

It is possible to observe in Fig. 7 that the values of average power obtained were always smaller for the CBN GS wheel. This can be explained by the fact that the most friable wheel produces sharp new edges more frequently, making the cutting easier and, consequently, the average power values lower. It is interesting to observe that, although the wheel wear was more accentuated on the GS wheel, the effect of the higher friability prevailed and the average power measured was lower than the values obtained with the GL wheel.

Regarding the feed rate, the power generated using the CBN GS wheel varied more than that using the CBN GL wheel, indicating that the friability of the CBN GS wheel reduced the power required for effective cutting more effectively when the wheel is subjected to lower forces. Conversely, in more severe conditions, within the range analyzed, greater friability reduced the required power to a lesser extent.

Trend lines were created for the power values against feed rate for each grinding wheel, based on the average power data. The efficiency of each wheel at feed rates on the proximity can be compared and estimated based on the power required, using the line equation provided by the software. Fig. 8 shows the linearized curves for each wheel.

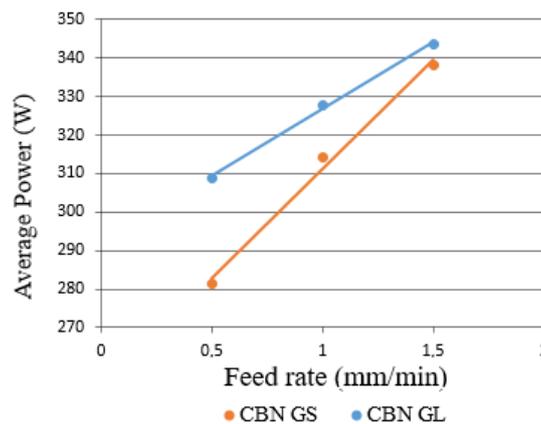


Figure 8. Linearized curves of the average power per feed rate for each wheel.

In Fig. 8, it can be seen that the slope of the linearized curve relative to the CBN GL grinding wheel is smaller than that of the CBN GS wheel, indicating that the increase in feed rate causes a higher variation in the average power required by the CBN GS wheel. Assuming that the linearized curves of the feed rates follow this slope up to the point they cross each other, it can be seen that they meet approximately at the point where the feed rate is 1.7 mm/s. Therefore, from this point on, the average grinding power of the CBN GS wheel will probably be higher than that of the CBN GL wheel. This also means that the CBN GL wheel is the best choice for more severe grinding conditions, while the CBN GS wheel removes material more easily at lower grinding forces.

4. CONCLUSIONS

Grinding using a tougher wheel (called GL in this work) generated lower surface roughness of workpieces and lower wheel wear than grinding with a more friable wheel (called GS in this work). On the other hand, the tougher wheel consumed higher cutting power than the more friable one;

As it was predicted by the literature, the increase of feed rate caused increase of surface roughness and wheel wear. The increase of feed rate also increased the consumption of power, but in a rate much smaller than the own feed growth, indicating that to cut using high feed is more energetically efficient than with low feed rate;

An analysis of the parameters allows to conclude that for applications where high stock removal and high forces combined with good surface finish are required, the CBN GL grinding wheel is much likely to be a better choice. However, in applications where free cutting and lower grinding power are desired in conditions with low forces, probably the CBN GS grinding wheel would fit better.

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